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Estimation of the operational characteristics and determination parameters of the vertical radial-axial hydraulic turbine type 400

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Abstract. The operational characteristic of the hydraulic turbine is an important document with the help of which would be carried out the control over the correct operation of a hydraulic turbine at a hydroelectric power station. This article presents the calculation of operational characteristic and determination of parameters of the vertical radial-axial hydraulic turbine (Francis turbine) for high heads type 400–500. In this study, the multiple mathematics used in computer which was written in Fortran language. We designed the operational characteristic and calculated the flow part of the runner. In addition, we determined the synchronous frequency of rotation of the hydraulic turbine with a one-dimensional method. The purpose of this work is to analyze the spatial structure of the flow in high-pressure hydraulic Francis turbines of the 400-500 types. Results of this computational and designing analysis can be useful for researchers to apply the present approach to calculate the operational characteristics and the parameters of the high-pressure hydraulic turbines.

1. Introduction

In the process of designing hydroelectric power plants, when choosing types of turbines and determining their main parameters, sizes, speed, efficiency, plant mark and other factors, as well as when assigning the most appropriate conditions for using the equipment during operation, it is necessary to have sufficiently complete data on the properties of turbines[1, 2]. These data are presented in the form of characteristics that determine all the necessary turbine performance for various conditions of its operation. Operational characteristics have two determining parameters and represent the dependence of this indicator on two independent variables. There are several types of common characteristics, with the name given in variables.

For high-pressure hydropower plants (more than 400 m) can be used active and reactive hydraulic turbines [3]. Hydraulic turbines using only kinetic flow energy are called active if using at least partially the potential pressure energy it would be called reactive turbine. The energy conversion process in these turbines occurs at an inlet pressure, which is greater than atmospheric pressure. Water is supplied to the runner in impulse hydraulic turbines through nozzles, in reactive ones through a guide vane. In an impulse hydraulic turbine, the pressure of the water in the inlet and outlet of the turbine's runner is equal to the atmospheric pressure [4, 5].

The main tasks of this analysis are to compute the vertical radial-axial hydraulic turbine (Francis turbine) of type runner 400, design the operating characteristic and the flow part of the turbine such as runner and synchronous frequency of rotation of the turbine with a one-dimensional method.

2. Materials and Methodologies

2.1. Determination of the main parameters of the hydraulic turbines

Aggregate (unit) capacity is determined [6, 7]:

$$N_{unit} = \frac{N_{HPP}}{Z_{unit}}, \quad (1)$$

where N_{unit} – unit capacity, MW; N_{HPP} – HPP capacity, MW; Z_{unit} – number of units, pcs.

Turbine capacity is determined:

$$N_T = \frac{N_{unit}}{\eta_{gen}}, \quad (2)$$

where N_T–turbine capacity, MW; η_{gen} – generator efficiency. For powerful units is assumed equal efficiency, $\eta_{gen} = 0.98$.

Hydraulic turbine impeller diameter:

$$D_1 = \sqrt{\frac{N_p}{9.81 * Q'_{I_p} * \sqrt{H_p} * \eta_N}}, \quad (3)$$

where D_1 – the diameter of the impeller, m; N_p – calculated power, kW; Q'_{I_p} – reduced discharge at the calculated point, m^3/s; H_p – calculated (design) head, m; η_M – Full-scale turbine efficiency at the calculated point is equal to $\eta_H = 0.92$, and then specify it.

For a radial-axial turbine (Francis turbine), the magnitude of the reduced discharge is taken from the output limit line of the hillchart (hill diagram). On a horizontal is the calculated point, which crosses several revolutions above optimum of the hillchart. Take $Q'_{I_p} = 280$ and $\eta'_{Ip} = 62.4\ min^{-1}$.Further, the calculated value of the runner's diameter would be normalizedD_1=4.5 m. Full-scale turbine efficiency specifies at the calculated point.

$$\eta_{N_p} = 1 - \left(\left(1 - \eta_{мр}\right) \cdot \left(\left(1 - \chi\right) + \chi \cdot \sqrt[5]{\frac{\text{Re}_м}{\text{Re}_н}} \right) \right) \quad (4)$$

where η_{M_P}– model-test turbine efficiency at the calculated point; $\eta_{M_p} = 0.8848$; χ – recounted share of losses (χ = 0.75); D_{1M} – model-test impeller diameter, m; $D_{1M} = 0.8,$ m.

Model-test turbine Reynolds number

$$\text{Re}_M = \frac{D_{1M}\sqrt{H_M}}{\nu}, \quad (5)$$

H_M – head on a model hydroturbine, m; H_M = 4.9 m;

Full-scale hydraulic turbine Reynolds number

$$Re_н = \frac{D_{1н}\sqrt{H_н}}{\nu}, \quad (6)$$

ν – kinematic coefficient of viscosity:

$$\frac{Re_м}{Re_н} = \frac{\upsilon_н \cdot D_{1м} \cdot \sqrt{H_м}}{\upsilon_м \cdot D_{1н} \cdot \sqrt{H_н}}, \tag{7}$$

First approximation:

$$\eta_{H_p} = 1 - \left((1 - 0.8848) * \left((1 - 0.75) + 0.75 * \sqrt[5]{0.01553}\right)\right) = 0.9336$$

The accepted calculated point ($Q'_{1p} = 840$ l/s) disagree with the calculated values of D_1. Specify the calculated point position.

$$Q'_{I_p} = \frac{N_p}{9.81 * D_1^2 * H_P \sqrt{H_p} * \eta_H}, \tag{8}$$

2.2. Determination of synchronous hydroturbine speed

Synchronous hydroturbine speed is determined by the known quantity of calculated (design) head and accepted values of corrected speed $n'_{I\,p}$ and impeller diameter *D₁*:

$$n = \frac{n'_{Ip} \cdot \sqrt{H_p}}{D_1}, \tag{9}$$

where n'_{Ip} corrected speed at the calculated point, min^{-1}.

$$n = \frac{62.4 * \sqrt{325}}{4.5} = 250 \ min^{-1}$$

The received value is synchronous.

Determine the correction for the speed of full-scale hydraulic turbine:

$$\Delta n'_I = n'_{Iopt.} \left(\sqrt{\frac{\eta_{H_{opt.}}}{\eta_{M_{opt.}}}} - 1 \right), \tag{10}$$

where η_{opt} – full-scale turbine efficiency in optimum; η_{opt} – model-test turbine in optimum; $\eta_{H_{opt}} = 0.902$.

The correction $\Delta n_I = 1.38$ is less than 3%, and beyond calculation is ignored.

Determine the corrected speed value at the highest and lowest heads:

$$n'_{I_{\min}} = \frac{n \cdot D_1}{\sqrt{H_{\max}}}, \tag{11}$$

$$n'_{I_{\max}} = \frac{n \cdot D_1}{\sqrt{H_{\min}}}, \tag{12}$$

3. Results

3.1. Construction of working and operating characteristics Francis turbine type 400

The energy and cavitation qualities of a full-scale turbine at various operating modes are presented in the form of an operational characteristic. The operational characteristic is an important document in which the proper operation of a hydroturbine at the HPP is monitored. The operational characteristic of turbine would built by using the universal characteristics of hydraulic turbine (Francis turbine) 400.

3.2. Operational characteristic calculation

Characteristic calculation is performed for three heads: $H_{\max}$, H_p and $H_{\min}$.

The program is written in Fortran language.

On the programme [7]:

Efficiency is recalculated using the following formula:

$$\eta_н = 1 - \left((1-\eta_м) \cdot \left((1-\chi) + \chi \cdot \sqrt[5]{\frac{Re_м}{Re_н}} \right) \right) \tag{13}$$

Full-scale turbine capacity (power) is computed using the following formula:

$$N_H = 9.81 * Q * H * \eta_H = 9.81 * D_1^2 * H * \sqrt{H} * Q_I * \eta_H$$

During recalculation accept $Q'_{Iн} = Q'_{Iм}$.

The suction height is measured from midline of the wicket gate to the level of the downstream. The suction height is determined by the formula:

$$H_s = H_{ATM} - H_d - \sigma_T H_p + \frac{b_0}{2} - \frac{\nabla}{2} - 1.5 \tag{14}$$

For operational characteristic calculation the source data are necessary. Source data are presented on print Q'_1, σ_T, $\eta_м$ for heads $H_{\min}, H_p, H_{\max}$.

SOURCE DATA

'For operational characteristic construction'

Model diameter D1m = 80000 m
Modal tests head H_m= 4.90 м
Water temperature during model tests t_m = 7.00 grad.
Modal max. efficiency K_m =9020
Full-scale turbine diameter D1 = 4.50000 m
Station heads:
maximumHmax = 404.00 m
calculated H_c = 325.00 m
minimal Hmin = 280.00 m
mean annual water temperature at the station tn = 20.00 grad.
reduced discharge at the calculated point Q11P = .2800 m^3/s
optimal reduced discharge Q11opt = .2350m^3/s
optimal reduced speed nmopt = 62.40 rev./min.
synchronous speed nc = 250.00 rev./min.
Wicket gate height B0 = .45m
Turbine axis mark
above sea level C = .00m
Values Km, Q11 and S for heads: Hmin, Hp and Hmax.

3.3. Operational characteristic construction

Having received the calculation results, move to the construction of operational characteristic.

Construct a full-scale turbine operating characteristic for the three heads: $H_{\max}$, H_p and $H_{\min}$ at a constant speed (Figure 1).

Construction output limit line for the capacity of hydraulic turbine (Figure 3). Output limit line is a composite of two sections: *vertical, incline*.

Vertical section- from the calculated to the maximum head – represents the power turbine limitation for the selected hydrogenerator nominal power.

Cutting the operational characteristic through horizontal lines $\eta = \text{const}$ that need to be drawn with an interval of 0.5%. Points of equal efficiency are transferred to the field of operational characteristics and connected by smooth curves, as a result we get lines of equal efficiency (Figure 3).

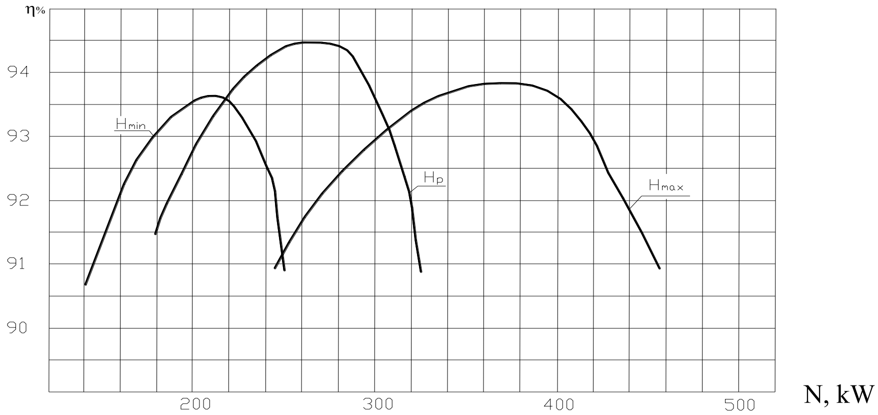

Figure 1. Full-scale turbine operating characteristic $\eta = f\left(N\right)$

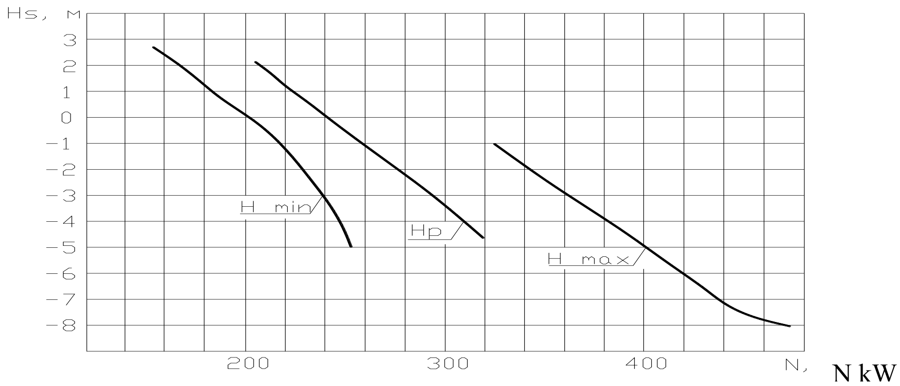

Figure 2. Curves $H_s = f\left(N\right)$ for specified heads.

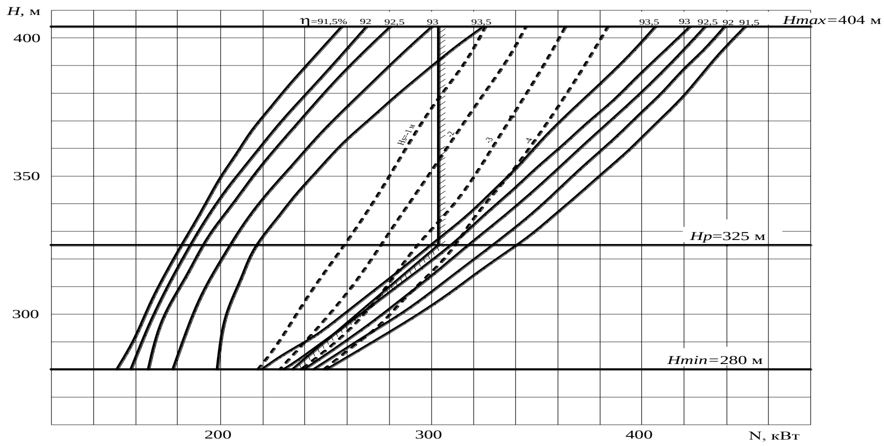

Figure 3. Operational characteristic.

N, kW

Plot curves $H_s = f\left(N\right)$ for specified heads (Figure 2). Cut curves $H_s = f\left(N\right)$ through horizontal lines with 1 m, in order to determine the capacity values for various heads for which $H_s = \text{const}$. By transferring the resulting points to the operational characteristic field and plot curves $H_s = \text{const}$.

Inclined section- from the calculated to the minimum head – its power limitation of turbine.

Determination of the value $Q_I^{'}$ in the cross point line $n_{\text{I}max}^{'} = \text{const}$ with the line $a_{0_p} = \text{const}$. At this point $Q_I' = 0.27\ m^3/s$ and $\eta_M = 0.88$ ($\eta_M = 0.9304$). Determination of the capacity of full-scale turbine with the lowest head.

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$$N_p = 9.81 * D_1^2 * H_{min} * \sqrt{H_{min}} * Q_I * \eta_H,$$

Upon recommendations for heads with the 402 meter height and received values of water discharges its necessary to arrange for the radial-axial hydraulic turbines type 400.

Conclusions

The vertical radial-axial hydraulic turbine (Francis) could be designed for a wide range of heads and flows, it is the most widely used turbine in the world. In this study, we present the calculation of the operational characteristic of the vertical radial-axial hydraulic turbine type 400 (Francis turbine). Also, constructed flow parts: runner of the unit (aggregate) and computed synchronous frequency of rotation turbine with one-dimensional method. Analysis for structure of the flow was carried out in the flow parts of the hydraulic Francis turbine types 400–500.

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